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SPATIAL AND TEMPORAL ANALYSIS OF CAPE, LEVEL OF FREE CONVECTION AND EQUIVALENT TEMPERATURE IN 2022 ACROSS THE INDIAN SUBCONTINENT

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ABSTRACT: *The atmosphere continues to be alive with a wide variety of events, many of which are created at random. Convective Available Potential Energy (CAPE), Level of Free Convection (LFC), pressure, and equivalent temperature are among the variables that are always changing. Understanding potential climate shifts requires research on thermodynamic settings that allow convection. In this study, we used data from four chosen stations (Chennai, Nagpur, Kolkata, and New Delhi) in 2022 to compare the daily, monthly, and seasonal changes of convective characteristics. Because variations in CAPE are associated with changes in convective activity and atmospheric energy balance, they could be an indicator of climate change. Additionally, the analysis of LFC sheds light on how easily convection can be started, and the comprehension of the troposphere's moisture and heat content is aided by comparable temperature fluctuations. Finding patterns that link local convective processes to more general monsoonal variability, extreme weather events, and long-term climate signals may be made easier by the findings.*

KEYWORDS: *Equivalent temperature, Level of Free Convection, and Convective Available Potential Energy*

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1. INTRODUCTION

The transfer of radiation from the sun to the earth is the basic physical process that drives the atmosphere. Interpreting the earth-atmosphere system's radiative processes and radiative energy balance is also essential to understanding climate and the factors that contribute to its changes. Regarding radiative processes, the dynamics and composition of the lower and upper atmosphere play a crucial role *[https://www.worldbank.org/en/news/feature/2013/06/19/india-climate-change-impacts].* The primary focus will be on the dynamical interactions between the various atmospheric layers and the movement of momentum and trace components between them. For precise climate modelling and weather pattern prediction, an understanding of atmospheric coupling processes is necessary. With an emphasis on interactions between various atmospheric layers and the exchange of energy, momentum, and mass, this research offers an understanding of the complex mechanisms driving atmospheric coupling. Through an examination of past data and research, we pinpoint the primary mechanisms and constituents impacting atmospheric coupling, such as radiative transfer, convection, and wave energy. *[Rohit Chakraborty ., et al,2017]*

1.1. Convective Available Potential Energy (CAPE)

CAPE can be estimated by vertically integrating the parcel buoyancy between the level of free convection (LFC) and level of neutral buoyancy (LNB), and thus it measures the maximum kinetic energy per unit air mass achievable by the convection of moist air from the sub cloud layer, assuming undiluted ascent, and gives an upper limit to the cumulus updraft vertical velocity*[A. Narendra Babu .,et al,2009]*.A highly unstable environment is indicated by high CAPE levels, which are generally linked to the possibility of severe weather, tall cumulonimbus clouds, and powerful updrafts. Because of the intense solar heating and the slow accumulation of surface moisture, CAPE frequently rises in India during the pre-monsoon months.Once a parcel is unstable, it will continue traveling vertically up or down until it hits a stable layer, however forces like gravity or momentum may cause it to overshoot. Depending on the origin and depth of the parcel, there are different types of CAPE that quantify this instability, including SBCAPE, MLCAPE, MUCAPE, DCAPE, and NCAPE *[Thompson et al., 2003].* The density of vertically displaced fluid elements is affected by adiabatically compressed or expanded fluid elements. They revert to their initial position, signifying convective stability, if their density fluctuates less than that of the surrounding air. They keep moving, showing convective instability, if the density fluctuates further. This is known as static instability because, in contrast to dynamic instability, it is independent of air motion.

The fundamental idea behind CAPE is buoyancy. Warm air close to the surface is less dense than colder air higher up in an unstable atmosphere. The warm air is able to rise as a result of the upward force this produces. The air cools and expands as it rises. The rising air parcel will keep rising if it is warmer than the surrounding air, absorbing energy from its surroundings and encouraging the formation of clouds. Cumulus or cumulonimbus clouds, which are frequently linked to thunderstorms, may form because of this upward movement. The potential for storm development rises with the overall energy available for these upward movements, which is measured by CAPE *[Emanuel, 1994].*In coastal regions, where CAPE plays a significant role in thunderstorm development, the effects of warmer ocean temperatures due to climate change could increase the frequency and intensity of tropical storms and cyclones. Warmer oceans provide more latent heat to fuel convection, increasing the likelihood of severe weather events. Moreover, the monsoon systems in places like India may also see altered convection patterns due to the changing thermal gradients between land and sea, influencing CAPE values and storm dynamics *[Goswami et al., 2006].* CAPE may be expressed as follows:

$$CAPE = \int_{p_f}^{p_n} R_d \left(T_{vp} - T_{ve}\right) d \ln p$$

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where T_{vp} is the virtual temperature of a lifted parcel moving upward moist adiabatically from the level of free convection to the level of neutral buoyancy, T_{ve} is the virtual temperature of the environment, R_d is the specific gas constant for dry air p_f is the pressure at the level of free convection, and p_n is the pressure at the level of neutral buoyancy. The dynamics of CAPE are being impacted by the consequences of climate change. Convective storms may become more common and violent as a result of rising CAPE values brought on by rising global temperatures and increased atmospheric moisture. It is anticipated that this change may lead to an increase in extreme weather phenomena, such as severe thunderstorms, flooding, and disturbances of the regular seasonal weather patterns. By integrating long-term climate data into short-term forecasting systems and enhancing numerical models for more accurate CAPE predictions, meteorologists are responding by improving their forecasting techniques.

1.2. Level of Free Convection (LFC)

The Level of free convection is the height at which an air parcel lifted dry adiabatically until saturated and then moist adiabatically thereafter, would first become warmer (less dense) than the surrounding environmental air. It is the altitude in the atmosphere where the temperature of the eniviornment decreases faster than the moist adiabatic lapse rate of a saturated of the air in the same level. The parcel would then continue to rise freely above this level until it becomes colder (denser) than the surrounding air. The level of free convection (LFC) is the altitude in the atmosphere where an air parcel lifted adiabatically until saturation becomes warmer than the environment at the same level, so that positive buoyancy can initiate self-sustained convection
[https://glossary.ametsoc.org/wiki/Level_of_free_convection_(LFC)].
The level of free convection (LFC) is found to increase considerably in all Indian subdivisions. Consequently, the coastal regions (particularly the western coast) experience increases in severe thunderstorms (TSS) and severe rainfall (SRF) frequency in the pre-monsoon period, while the inland regions (especially Central India) experience an increase in ordinary thunderstorms (TSO) and weak rainfall (WRF) frequency during the monsoon and post-monsoon periods[*Camuffo, D.2014].*

Further, the LFC exhibits diurnal fluctuation, a pattern of change during the day. The sun heats the surface during the day, particularly in the afternoon. The LFC decreases as a result of the air rising more readily due to this warmth. At night, when the surface cools, the air is less likely to rise, hence the LFC gets higher. Because the LFC is lower and easier to reach in the afternoon or early evening, thunderstorms are more likely to occur during these times. The LFC is also impacted by seasonal variations. The air is warmer and more humid during the monsoon season, particularly in India. As a result, thunderstorms occur often and the LFC remains low. Because the air is more stable during dry seasons, the LFC remains high or does not form as readily, which lowers the likelihood of storms. Moisture-rich air can be swiftly forced upward by large weather systems like tropical cyclones or fronts. This increases the likelihood of storm activity and heavy rainfall by lowering the LFC and making the atmosphere more unstable.

1.3. Equivalent Temperature

Equivalent temperature can be used to compare the temperature of air parcels that are at different levels in the troposphere. Temperature tends to decrease with height**.**

$$T_{ie} = T\left(1 + \frac{L_w}{c_p\, T}\right)$$

where T_{ie} is the isobaric equivalent temperature, T the temperature, w the mixing ratio, L is the latent heat, and c_p is the specific heat of air at constant pressure.The equivalent temperature T_e (or t_e) *or* isobaric equivalent temperature is the temperature that a moist air parcel would have if all water

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vapour in it were condensed out at constant pressure and adiabatically, *i.e.,* all the latent heat released in the condensation is used to heat the air. Equivalent potential temperature, commonly referred to as theta-e , is a quantity that is conserved during changes to an air parcel's pressure (that is, during vertical motions in the atmosphere), even if water vapor condenses during that pressure change. It is therefore more conserved than the ordinary potential temperature, which remains constant only for unsaturated vertical motions (pressure changes) potentially leading to cloud growth or storm development. [*Chakraborty, R,et al.,2019].*The equivalent potential temperature can then be calculated using a more complete expression:

$$\theta_e = \theta_L \cdot \exp\left[\left(\frac{L_v r}{c_p T_L}\right)(1 + 0.81r)\right]$$

Or, in Bolton's widely-used approximation

$$\theta_e = \theta_L \cdot exp\left[\left(\frac{3036}{T_L} - 1.78\right) . r \cdot (1 + 0.448r)\right]$$

Where

θ_L=potential temperature at LCL

T_L=temperature at LCL

L_v=latent heat of vaporization(2.5×10^6J/kg)

Cp = specific heat at constant pressure(1004 J/kg.K)

r = mixing ratio(kg/kg)

To better assess the stability of moist air, meteorologists use a concept called equivalent potential temperature (θ_e). This metric extends the idea of potential temperature by also factoring in the latent heat released during condensation. It provides a more complete measure of the energy content of a moist air parcel. For saturated air, or for unsaturated air expected to reach saturation upon lifting, stability requires that equivalent potential temperature increases with height. If it decreases, the atmosphere is considered conditionally unstable, and vertical motions such as convection or thunderstorm formation are likely to occur. Under stable & stratified conditions, the potential temperature increases with height, which suppresses vertical motions.

$\partial\theta e/\partial z > 0$

If the equivalent potential temperature decreases with height, the atmosphere becomes unstable to vertical motions, making convection likely. Such situations, where the equivalent potential temperature decreases with height and indicates instability in saturated air, are commonly observed *[Wallace & Hobbs, 2006; Emanuel, 1994; AMS Glossary].*

$\partial\theta e/\partial z < 0$

Thus, θ_e is an essential tool in evaluating moist atmospheric stability. In the mesoscale, equivalent potential temperature serves as a useful indicator of the static stability of an unsaturated atmosphere.

2. DATA ANALYSIS

This study analysed Radiosonde data from the Wyoming University data archive, for the parameters CAPE, LFC and Equivalent temperature spanning January 1,2022, at 00 UTC to December 31, 2022, at 12 UTC. For further analysis, the averages of these two-time intervals were taken, and separate plots were created, showing the variation of each parameter over the study period for all the four stations over Indian region (Chennai, Nagpur, New Delhi, and Kolkata). Additionally, daily and monthly average data were used to study the seasonal variation of parameters, focusing on

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the changes in CAPE, LFC and equivalent temperature during the four seasons of 2022. Rainfall data is taken from the Indian Meteorological Department (IMD) gridded data in 2022, of very high spatial resolution (0.25^0 x 0.25^0). (https://weather.uwyo.edu/upperair/sounding.html.) The current communication uses daily radiosonde data gathered over the four chosen stations of Chennai, Nagpur, Kolkata, and New Delhi throughout the year 2022.

2.1 The domain of investigation:

As illustrated in Figure 2.1, the four Indian stations Chennai, Nagpur, Kolkata, and New Delhi constitute the subject of this study. Each station plays a unique role in shaping the climatic patterns and corresponding human activities in its region.

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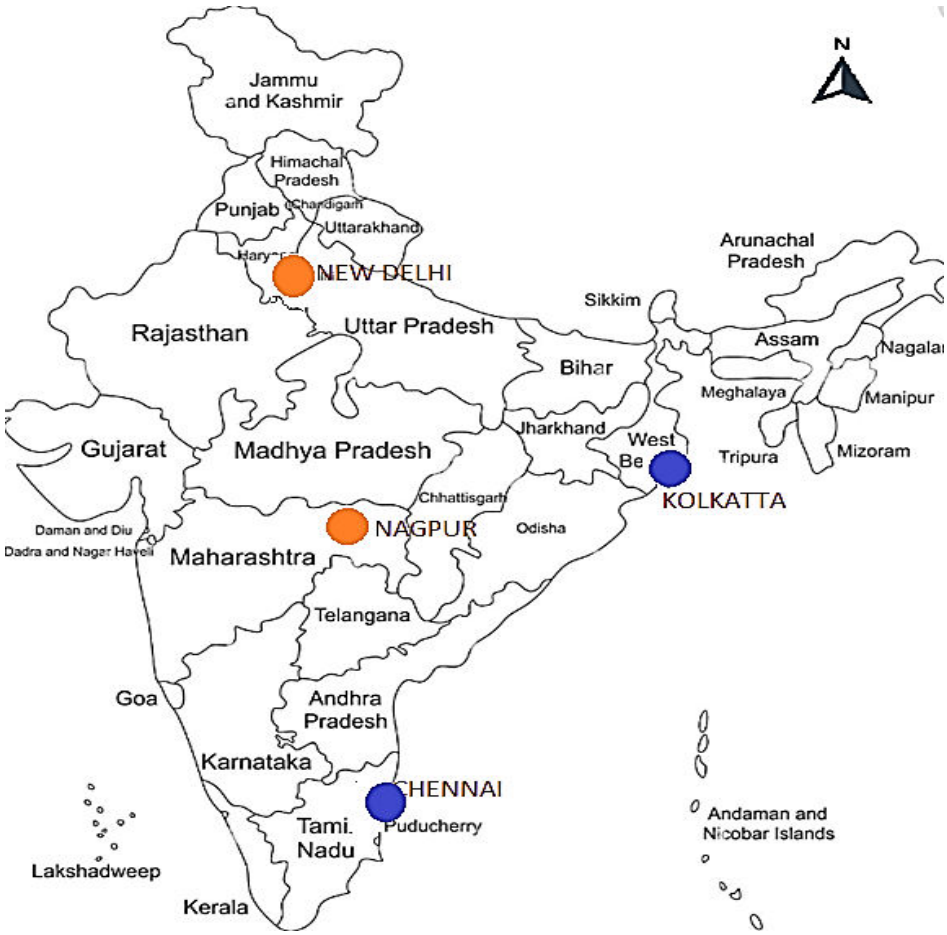

Figure 2.1: Geographical locations of study stations in India- Chennai and Kolkata (coastal stations);Nagpur and New Delhi(inland stations).

3. RESULTS AND DISCUSSIONS

3.1 Diurnal variation of parameters over the selected stations in 2022

The figure depicts the daily changes of three important convective parameters over the four distinct stations, represented by panels (a) Chennai, (b) Nagpur, (c) Kolkata and (d) New Delhi respectively. These data series provide information on the day-to-day variations and temporal behaviour of convective conditions at each site over the course of a year. The absence of atmospheric sounding data on some days results in noticeable data gaps . To overcome this constraint and give a more comprehensive image, monthly-mean plots are also produced, enabling more seamless representation and enhanced continuity in the study.

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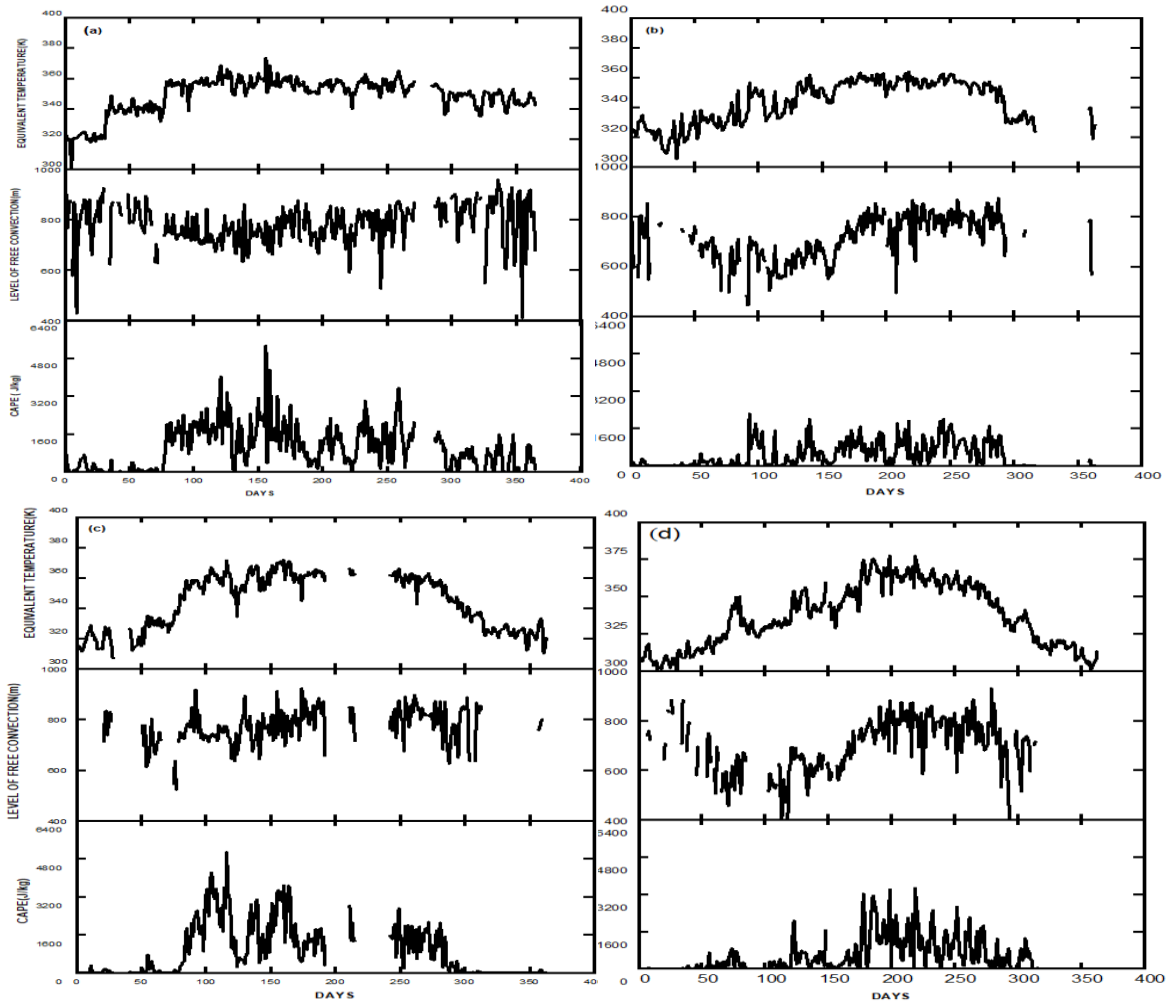

Figure 3.1: Day to day variation of CAPE,LFC and equivalent temperature over the selected stations,in the year 2022(January1 to December31).

Figure 3.1(a) shows daily variation of CAPE at Chennai Station. The Radiosonde data sets are archived for 00UTC and 12UTC per day from January 1 to December 31 of 2022. CAPE was calculated two times in a day, and the daily CAPE was made of the average of these two values, which is again averaged for each month. Figure 3.1(b) shows daily variation of CAPE at Nagpur Station. Figure 3.1(c) shows daily variation of CAPE at Kolkata Station. Figure 3.1(d) shows daily variation of CAPE at New Delhi Station. During the pre-monsoon season, CAPE levels are often higher in Chennai and Kolkata, indicating a greater possibility for convective activity [*Riemann-Campe, K.et al.,2009].* Strong convection is indicated by the dramatic CAPE spikes seen in Nagpur and New Delhi. Reduced convective potential is shown by the lower CAPE at the end of the year. All stations have very erratic LFC values, particularly in the middle of the year. Particularly for Nagpur and New Delhi, there is a discernible rise in LFC prior to the start of the monsoon. Lower LFC values in Chennai and Kolkata indicate more stable atmospheric conditions when compared to inland sites. With greater temperatures around mid-year (presumably pre-monsoon and monsoon periods), all four sites exhibit a distinct seasonal variation.

3.2 Monthly variation of the selected parameters

The monthly variance of CAPE, LFC and Equivalent temperature for four distinct Indian stations in 2022 is depicted in the following figures. Averaging daily data for every month at every station yielded the monthly mean values of the parameters shown in the graphs.

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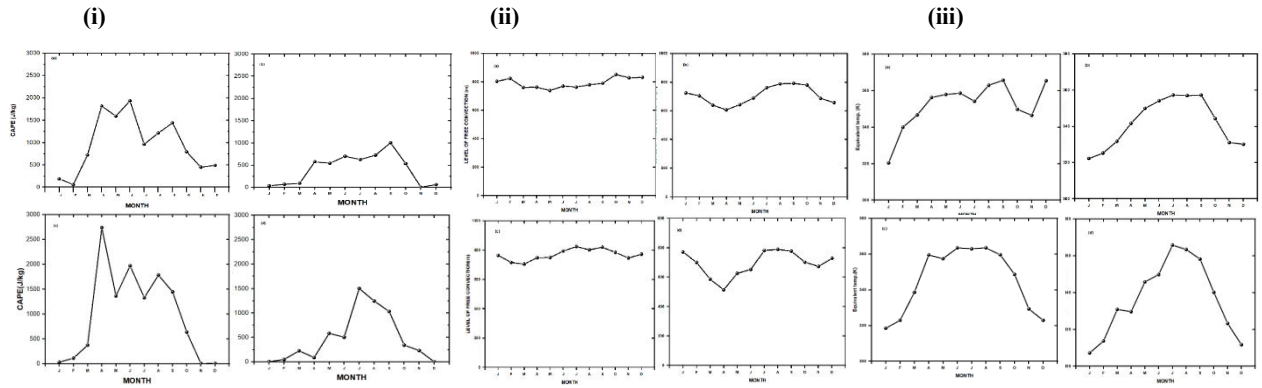

Figure 3.2: Monthly variation of (i)CAPE, (ii) LFC, (iii) equivalent temperature during 2022 over the study locations.

Convective instability and the likelihood of thunderstorm generation are evaluated using CAPE, a crucial meteorological quantity. CAPE is increasing from March and relatively high in May, June and July. Figure 3.2-i-(a) shows the monthly average values of CAPE in 2022, for Chennai station. Daily CAPE is increasing from early March, highest on early June in the year (1934.839 J/kg), decreasing gradually from September onwards. In the dry season (from December to February), daily CAPE is very low, and it goes to a minimum of 61.0841 J/kg in February. From March, CAPE is rising, reaching reasonably high points in the period April- September. The monthly average CAPE values for Nagpur station in 2022 are displayed in Figure 3.2-i-(b). Daily CAPE starts to rise in early March and reaches its peak in early September of the year (1003.4835 J/kg), before progressively declining in September. Daily CAPE is extremely low during the months January, February, November and December, with a minimum of 4.289 J/kg in November. CAPE began growing in March and reached an adequate peak between April and September. Figure 3.2-i-(c) shows the monthly average CAPE values over Kolkata station in 2022. Early in March, daily CAPE begins to increase. It peaks in April (2739.541 J/kg) and then gradually declines from September. January, February, November, and December have the lowest daily CAPE, with a minimum of 6.3643 J/kg in November. The CAPE commenced to rise in March and peaked between April and September. The monthly average CAPE values for the New Delhi station in 2022 are indicated in Figure 3.2-i-(d). Daily CAPE starts to rise in early April. It reaches its peak in July (1502.27 J/kg) and starts to progressively decrease from September, with a minimum of 0.094 J/kg in December.

Monthly values of LFC are the average of daily values. Figure 3.2-ii-(a) shows variation of monthly Level of free convection at Chennai .Two sets of Radiosonde data were taken during the time 00 UTC and 12UTC. Level of free convection was calculated two times in a day and the daily value was made of the average of these two values. Monthly Level of free convection is high in January, February, December with a peak of 851.743m. It decreases gradually from March to September months and attains a minimum of 738.92113m in May. In the months of September, October and November LFC is slightly higher than the previous months. The monthly fluctuations in the level of free convection at Nagpur Station, latitude: 21.10 ^{0}N , longitude: 79.05 ^{0} E, station elevation: 310.0 m is depicted in Figure 3.2-ii-(b).LFC has a high value in August,September,October,with a maximum value of 792.268m in September. The level of free convection is comparatively low in the month of April(607.29m). Figure 3.2-ii-(c) exhibits the monthly variability in the free convection level at Kolkata Station. April month has the highest value for LFC (824.85m). In March, the amount of free convection is rather low (705.39 m).The LFC increased starting in July and reached its highest point in August (789.29m) . Figure 3.2-ii-(d) shows the monthly average LFC values for the New Delhi station in 2022. Early July is when monthly LFC starts to increase. It starts to gradually decline in April, reaching a minimum of 514.577 m.

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Figure 3.2-iii-(a) is the analysis of the distribution of equivalent temperature at Chennai station.Data are considered for both morning and afternoon profile. Daily value was made of the average of these two values. From the plot it is clear that the equivalent temperature is low in the months of January and February with a minimum of 320.39K and relatively high in August and September, where the peak value is 365.73K. Season wise variation of the Equivalent temperature is drawn in Fig 3.7.The investigation of the variation in equivalent temperature at Nagpur station is shown in Figure 3.2-iii-(b).Both the morning and afternoon profiles' data are taken into account. The plot renders evident that the corresponding temperature is fairly elevated from June to September with a minimum of 322.23K and low in the months of January, February, November, and December,where the peak goes to 357.368K in July.Figure 3.2-iii-(c) depicts the analysis of the fluctuation in equivalent temperature at Nagpur station. The map makes it clear that the corresponding temperature is rather high from April to September, with a maximum of 363.46K in June and minimums of 318.49K in January, February, November, and December. The review of the variation in equivalent temperature at the New Delhi station is portrayed in Figure 3.2-iii-(d). The graphic representation clearly shows that the corresponding temperature is fairly high from July to October, reaching a maximum of 365.83K in July and a minimum of 307.2268K in January.

3.3 Seasonal variation

The average value of each parameter for each station have been calculated for the Indian subcontinent's four primary seasons; December, January through February is winter; March–May, the pre-monsoon season; June–August is Monsoon; September through November- the post- monsoon. This seasonal study aids in determining how variations in temperature, humidity, and broad atmospheric circulation patterns affect convective potential at each site throughout the year. Seasonal CAPE readings for Chennai in 2022 show a distinct seasonal pattern of convective potential variation. Wintertime sees the lowest CAPE values, which is indicative of stable atmospheric conditions. Because of strong convection and intense sun heating, they reach their peak during the pre-monsoon season. Due to rainfall and cloud cover, CAPE values remain moderate to high during the monsoon season. Relatively high CAPE levels during the post-monsoon season also point to lingering atmospheric instability. Nagpur's seasonal CAPE figures for 2022 reflect a clear pattern of seasonal changes in convective potential. The lowest CAPE values are observed throughout the winter, indicating stable atmospheric conditions. They peak in the pre-monsoon season due to strong convection and intense solar heating. During the monsoon season, CAPE values skyrocket due to rainfall and cloud cover. Indicators of persistent atmospheric instability during the post-monsoon season include relatively high CAPE levels.

(i) **(ii)** **(iii)**

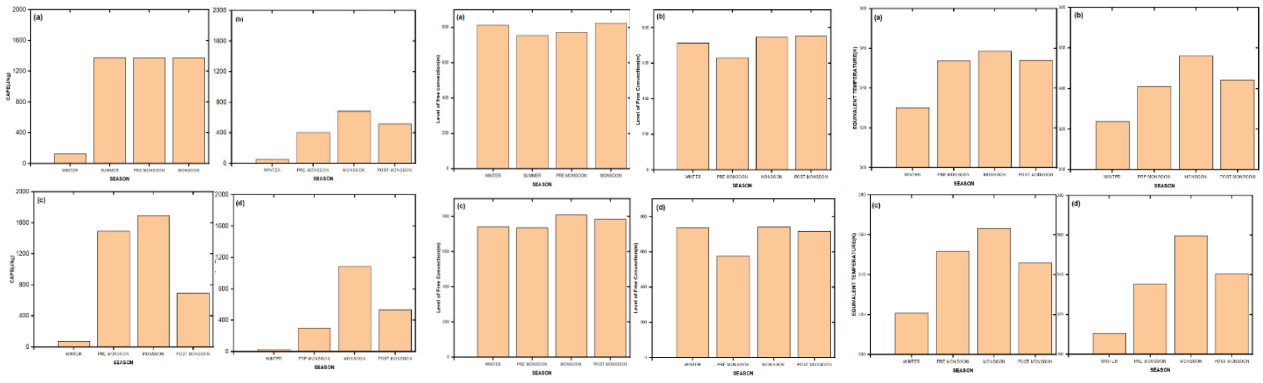

Figure 3.3: Seasonal variation of (i)CAPE, (ii) LFC ,(iii) equivalent temperature during 2022 over the study locations.

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The analysis of Kolkata's seasonal CAPE values in 2022 reveals distinct patterns associated with atmospheric convection. Winter shows the lowest CAPE levels, indicating calm weather, while the pre-monsoon season features the highest values due to strong solar heating and convective activity. The monsoon season maintains moderate to high CAPE levels owing to moisture and frequent thunderstorms, while the post-monsoon period suggests ongoing atmospheric instability with relatively high CAPE values. Understanding these seasonal variations is vital for predicting Kolkata's weather and potential extreme weather events.*[Murugavel, P.,et al.,2012].*The 2022 seasonal variation of LFC indicates that winter has low convective activity and stability, while the pre-monsoon period shows heightened convective potential and instability. Monsoon conditions maintain low to moderate LFC values, leading to frequent thunderstorms and heavy rains. The study also highlights equivalent temperature patterns in Chennai, Nagpur, Kolkata, and New Delhi, with winter having lower temperatures due to stable conditions, pre-monsoon experiencing higher temperatures from solar heating and moisture, and monsoons maintaining high temperatures owing to rainfall and moisture-related thunderstorms.

4. CONCLUSION

Convective Available Potential Energy, Level of Free Convection and Equivalent temperature are all thoroughly analysed spatially and temporally over the selected stations in the Indian subcontinent in 2022. The study demonstrates the seasonal trends of these interconnected atmospheric factors and their important function in regulating precipitation distribution and convective activity. Chennai's CAPE values show a fluctuating pattern from January to March, with a sharp increase from April, moderate fluctuations from July to October, and a decreasing trend from November to December. Nagpur and Kolkata show low CAPE values in January and February, gradually increasing from March. Moderate peaks occur between June and September, with rapid decline in November and December, suggesting a monsoon-driven influence. The CAPE in New Delhi fluctuates from low until March, then sharply increases in May-June, then declines gradually, peaking during the monsoon months and rapidly decreasing from October. Chennai and Kolkata show strong pre-monsoon CAPE peaks, while Nagpur and New Delhi show monsoon-driven increases. Kolkata has sustained CAPE through the monsoon, with a sharpest peak in May.

According to the findings, CAPE and LFC show significant regional and seasonal fluctuation, with larger values being recorded during the monsoon months. These results are further supported by the equivalent temperature patterns, which provide a useful thermodynamic indicator of convective strength and latent heat release. The significance of CAPE as a diagnostic and prognostic tool for severe weather can be explained by the noteworthy spatial association between CAPE and rainfall. This assumes that areas with consistently high CAPE values typically experience more intense precipitation occurrences**.** Overall, the results highlight how useful it is to combine several atmospheric characteristics to better understand and predict convective weather systems in a region with a variety of climates, such as the Indian subcontinent. To further improve predictive capabilities and help climate resilience measures, future work can expand this analysis to multi-year datasets and include high-resolution satellite or model-based reanalysis outputs.

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